Timing and spectral studies of the transient X-ray pulsar EXO 053109-6609.2 with ASCA and Beppo-SAX

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ABSTRACT

We report timing and spectral properties of the transient Be X-ray pulsar EXO 053109–6609.2 studied using observations made with the ASCA and Beppo-SAX observatories. Though there must have been at least one spin-down episode of the pulsar since its discovery, the new pulse period measurements show a monotonic spin-up trend since 1996. The pulse profile is found to have marginal energy dependence. There is also evidence for strong luminosity dependence of the pulse profile, a single peaked profile at low luminosity that changes to a double peaked profile at high luminosity. This suggests a change in the accretion pattern at certain luminosity level. The X-ray spectrum is found to consist of a simple power-law with photon index in the range of 0.4–0.8. At high intensity level the spectrum also shows presence of weak iron emission line.

Subject headings: stars : neutron — Pulsars : individual (EXO 053109–6609.2) — X-rays : stars

1. Introduction

The two Magellanic Clouds have larger number density of High Mass X-ray Binaries (HMXB) compared to our galaxy. The Small Magellanic Cloud (SMC) with a mass of about 1% of our Galaxy has a total of about 70 HMXBs and HMXB candidates, almost comparable to that in our galaxy (Haberl & Sasaki 2000; Yokogawa et al. 2003). Though the HMXB number density in the Large Magellanic Cloud (LMC) is not as high as that in SMC, it is still significantly higher than the Galactic value (Sasaki, Haberl & Pietsch 2000). In-spite

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of a large number of HMXB pulsar objects in the two Magellanic Clouds, individual objects have not been studied in great detail except for SMC X-1 and LMC X-4. There are four HMXB pulsars known in the LMC, of which LMC X-4 is the best studied. Several of these sources show a very large X-ray luminosity in their high states, close to or exceeding the Eddington limit for a 1 $M_{\odot}$ object. Sources, in which a strong local absorption column is absent, nature of the soft spectral component can be studied in detail. Due to a low galactic absorption column density towards the LMC and SMC, these objects are also suitable for study of the local absorbing material. A soft excess in the X-ray spectrum, now detected in several accreting pulsars can be a common feature of the HMXB pulsars. But since most of the HMXB pulsars are in the Galactic plane, large line of sight absorption usually makes it difficult to detect it. It is therefore, important to study details of the individual HMXBs in the LMC and SMC.

The transient Be X-ray binary source EXO 053109–6609.2 was discovered with the EXOSAT observatory in 1983 (Pietsch, Rosso & Dennerl 1989). Hard X-ray emission from this source was detected with the SL2 XRT experiment (Hanson et al. 1989) and its intensity variations were studied in detail with the ROSAT (Haberl, Dennerl, & Pietsch 1995). X-ray pulsations were also discovered with the ROSAT (Dennerl, Haberl & Pietsch 1995). This pulsar is located at a distance of 17′ from the luminous binary X-ray pulsar LMC X-4, and has a pulse period of 13.7 s, which is also close to the 13.5 s pulse period of LMC X-4. During a Beppo-SAX observation of LMC X-4, EXO 053109–6609.2 was in the field of view of the narrow field instruments of Beppo-SAX, and pulsations were detected along with a positive local period derivative (Burderi et al. 1998). The source was also observed with the XMM in 2000 during which it was in a relatively bright state (Haberl, Dennerl, & Pietsch 2003). The optical counterpart is one of the two close double Be-stars (Stevens, Coe and Buckley 1999)

In the subsequent sections we present the archival observations that we have used to study this source (§2), results from temporal and spectral analysis of the data (§3) and follow up this with a discussion on the nature of this pulsar (§4).

2. Observations

We have analysed archival data from four observations of the pulsar EXO 053109–6609.2. Three of these observations were made with the Beppo-SAX observatory and one with the ASCA.

The field of EXO 053109–6609.2 was covered by ASCA-GIS during several observations

of nearby sources. In one observation of LMC X-4, made during 1996 May 24–26, we found EXO 053109–6609.2 to be bright enough for temporal and spectral investigation. It was also present in the field of view of the Beppo-SAX narrow field instruments during two observations of LMC X-4 in 1997 (March 13–15) and 1998 (October 20–22) and in another one observation of the LMC in 2000 (January 01–02). EXO 053109–6609.2 was in a transient outburst during the 1997 observation and the pulsation properties during this period have been reported earlier (Burderi et. al. 1998). We have found 36 ks of useful exposure with ASCA-GIS, 117, 82 and 32 ks with SAX-MECS (1997, 1998 and 2000 respectively), and 42, 31 and 15 ks with SAX-LECS. For more details of these instruments, refer to Tanaka, Inoue & Holt (1994, ASCA) and Boella et al. (1997, SAX).

3. Analysis and results

We have used the standard data selection criteria of both the observatories. The count rates and spectra of the source were obtained from circular regions of radius $6'$ for ASCA-GIS, $3'$ for SAX-MECS and $2'$ for SAX-LECS. The corresponding background spectra were extracted from source free nearby regions in the respective FOVs.

3.1. Timing analysis

Light curves from these observations were extracted with time resolution of 0.25 s for SAX LECS and MECS and 0.50 s for ASCA-GIS. Barycenter corrections were applied to the photon arrival times in the event files before extraction of light curves. The pulse folding and χ^2 maximisation search near the expected pulse period of 13.7 s clearly showed presence of pulsations in all the observations. The new pulse period measurements with ASCA-GIS and Beppo-SAX LECS/MECS are given in Table 1 and plotted in Figure 1.

Pulse profiles were created from background subtracted light curves in different energy bands. The pulse profiles of all but the 1997 Beppo-SAX observation are shown in Figure 2 along with the dates of each observation and the 2–10 keV luminosity of the source during the corresponding observation. There is a hint of slight energy dependence of the pulse profile in the ASCA observation. The pulse profile clearly shows a luminosity dependence; a single peaked profile at low luminosity (ASCA 1996, SAX 1998, top panels of Figure 2.) and a double peaked profile at high luminosity. The pulse fraction is in the range of 30–60%.

The pulse period history of EXO 053109–6609.2, obtained by combining the new observations and the earlier reported measurements with the ROSAT, Beppo-SAX and XMM

observatories are plotted in Figure 1. An overall spin-down trend during the last five years and some local variation from this trend can be seen in the figure. The orbital elements of this binary system is not known, and we note that an orbital motion of the neutron star with a velocity of a few hundred km s^{-1} can also result in the observed changes in the local pulse period measurements.

3.2. Spectral analysis

3.2.1. ASCA

Suitable binning was applied to all the energy spectra before spectral fitting. We first fitted the ASCA-GIS spectrum with a simple model consisting of a power-law component and line of sight absorption with solar abundance of metals. The source was in a low intensity state during this ASCA observation. We rebinned the spectrum to 12 spectral bins in the 0.7–9.0 keV range. A photon index of 0.46 and equivalent hydrogen column density of 1.1×10^{21} atoms cm^{-2} was obtained with a reduced χ^2 of 0.23 for 9 degrees of freedom. Assuming a distance of 55 kpc to the LMC, the X-ray luminosity during the ASCA observation was 1.2×10^{36} erg s^{-1}. No signature of iron fluorescence was detected and a broad binning scheme needed due to the poor statistics also does not allow us to put a strong upper limit on the equivalent width of a line feature at 6.4 keV. The spectrum measured with ASCA-GIS is shown in Figure 3 along with the best fit model spectrum and the residuals.

3.2.2. SAX

In all the three Beppo-SAX observations, the source EXO 053109–6609.2 was at a distance of about $17'$ away from the centre of the field of view. Therefore, it was necessary to consider the smaller collecting area of the mirrors at large off-axis angles. For spectral analysis of MECS spectra at an off-axis angle of $17'$, we have taken an average of the effective areas at $14'$ and $20'$, which are available for the MECS. This is likely to introduce a few percent uncertainty in the measurements of spectral parameters over the statistical errors. At low energies, the relative loss of effective area for different off-axis angles is not energy dependent. Therefore, the LECS spectra were fitted with the on-axis effective area curve, and a relative normalisation with respect to the MECS was used. All the three Beppo-SAX observations were fitted with the same spectral model described above. In the 1997 and 2000 observations, there was some signature of an iron emission line, and a separate narrow Gaussian line at 6.4 keV was included in the model. The equivalent width of the iron line

during these two observations were 130 ± 50 eV and 180 ± 160 eV respectively. The spectral parameters along with the reduced χ^2 obtained are given in Table 2. The X-ray luminosities in the 2.0–10.0 keV band during the three SAX observations are 6.1×10^{36}, 3.0×10^{35}, and 1.5×10^{36} erg s^{-1} during the 1997, 1998 and 2000 observations respectively. The spectra measured with Beppo-SAX LECS and MECS instruments are shown in Figure 3.

4. Discussion

The pulsar EXO 053109–6609.2, like many other HMXB pulsars with Be star companions, is believed to be a transient source. However, we have found this pulsar to be bright, at a luminosity level of 3×10^{35} erg s^{-1} to 6×10^{36} erg s^{-1} in most of the X-ray observations made since 1993 with the low background imaging instruments. Several ROSAT observations during March to May 1993 also found the source to have significant X-ray intensity (Haberl et al. 1995). In this respect, this pulsar is more akin to 4U 1907+09 (In't Zand 1999, Mukerjee et al. 2001), which also shows intensity variations of similar scale but without any obvious transient phenomena. Its long term X-ray intensity behaviour is different from that of the Be-Star transients like EXO 2030+375 (Parmar, White & Stella 1989). The peak X-ray luminosity of 6×10^{36} erg s^{-1} observed in 1997 is however, much smaller than that of the pulsars SMC X-1 and LMC X-4 (Paul et al. 2002), which have high mass companion stars in very close orbits. This indicates a large size orbit and hence orbital period. The archival X-ray observations are not sufficiently long to search for pulse arrival time delay that can help to determine the orbital parameters. Analysing the RXTE-ASM light curve of EXO 053109–6609.2 we have found a peak in the power spectrum at 183 days and its integer multiples. Intensity variations of the bright nearby source LMC X-4 is unlikely to create this because the 30.5 day superorbital intensity variation of LMC X-4 is not reflected in the power spectrum of EXO 053109–6609.2. However, since this is very close to a half-year, yearly observational effects cannot be ruled out.

Combining the present observations with the earlier measurements of pulse periods with the ROSAT and the Beppo-SAX, we have obtained a period history of the pulsar, shown in Figure 1. It shows a clear monotonic spin-up trend since the ASCA observation in 1996, though not with a constant period derivative. However, certainly there were spin-down episodes between the 1991 ROSAT observation and the 1996 ASCA observation. A spin-down was also observed during the 1997 Beppo-SAX observation itself, which is a surprise considering the high intensity level during this observation. The last 5 years of pulse period measurements presented here shows a spin-up of the neutron star. This suggests that accretion onto the neutron star was in progress for at least a significant part of this period.

However, we cannot rule out a significant binary motion related component in the observed pulse period variations.

The X-ray emission from the polar cap regions can have different geometric pattern at different mass accretion rates. In the transient X-ray pulsar EXO 2030+375, a change in beaming pattern, from a fan beam in high luminosity state to a pencil-beam in low luminosity state was observed with the EXOSAT (Parmar et al. 1989). The pulse profiles of EXO 053109–6609.2 at different luminosity levels presented here and elsewhere (Burderi et al. 1998, Haberl et al. 2003) clearly indicate a dependence on the mass accretion rate. The pulse profile is single peaked and nearly sinusoidal in low intensity state (Beppo-SAX : 1998), and it has two distinct well separated peaks or an admixture of the above two during other observations. It is possible that in EXO 053109–6609.2 also, the X-ray beam pattern changes from a pencil beam at low luminosity to a fan beam at high luminosity. The change in beam pattern probably takes place at a luminosity level of $\sim 10^{36}$ erg s^{-1}.

During the ASCA observation in 1996 and the Beppo-SAX observation in 1998, the source was in low intensity state and the spectral parameters are not constrained well from these observations. However, the spectral characteristics reported here from the other three observations indicate intrinsic spectral variability in the pulsar. The power-law component of the spectrum is softer at higher luminosity.

The XMM spectrum of this source unambiguously showed the presence of a soft spectral component in excess of a partially absorbed hard power-law extended to lower energies (Haberl et al. 2003). The same observation also showed that the pulse profile is different in the soft and the hard X-ray bands. This indicates that the soft component may have a different origin, or at least the geometry of emission is different in different energy ranges. Presence of narrow features in the soft excess prompted Haberl et al. (2003) to use a hot plasma model that yields a temperature of 0.1 keV and emission measure of 4×10^{61} cm^{-3}. Such a plasma is unlikely to show pulsations due to its large physical size and large cooling time scale, contrary to what is seen in the 0.15-0.4 keV band. A blackbody type component with separate low energy emission lines as seen in Her X-1 (Endo et al. 2000) may be a better description of the soft excess of this pulsar. Several other accreting X-ray pulsars with relatively low line of sight absorption show soft excess (Paul et al. 2002 and references therein). In some sources the soft excess probably originates in a part of the X-ray irradiated inner accretion disk (Endo et al. 2000; Naik & Paul 2004). From independent analysis of the XMM spectra we have found that in EXO 053109–6609.2, the total luminosity of unabsorbed X-ray emission in the soft excess is 1.1×10^{36} erg s^{-1}, which is only about 1% of the total emission in the 1–10 keV energy band. The ratio of the soft excess flux to the total flux is smaller than that of SMC X-1 (3.6%), LMC X-4 (6.4%) and Her X-1 (10%). In this pulsar,

the size of the black body emission region is required to be only about 10^7 cm and, therefore, can easily be accommodated in inner part of the accretion disk heated by the hard X-rays.

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REFERENCES

Boella, G., Butler, R. C., Perola, G. C., Piro, L., Scarsi, L., Bleeker, J. A. M. 1997, A&AS, 122, 299

Burderi, L., Salvo, T. Di., Robba, N. R., Sordo, S. Del., Santangelo, A., & Segreto, A. 1998, ApJ, 498, 831

Dennerl, K., Haberl, F., & Pietsch, W. 1995, IAU Circ. 6184

Endo, T., Nagase, F., & Mihara, T. 2000, PASJ, 52, 223

in 't Zand, J. J. M., Baykal, A., & Strohmayer, T. E. 1998, ApJ, 496, 386

Haberl, F., Dennerl, K., & Pietsch, W. 1995, A&A, 302, L1

Haberl, F., Dennerl, K., & Pietsch, W. 2003, A&A, 406, 471

Haberl, F., & Sasaki, M. 2000, A&A, 359, 573

Hanson, C. G., Skinner, G. K., Eyles, C. J., & Willmore, A. P. 1989, MNRAS, 240, 1P

Mukerjee, K., Agrawal, P. C., Paul, B., Rao, A. R., Yadav, J. S., Seetha, S., & Kasturirangan, K. 2001, ApJ, 548, 368

Naik, S., & Paul, B. 2004, ApJ, 600, 351

Parmar, A. N., White, N. E., & Stella, L. 1989, ApJ, 338, 373

Paul, B., Nagase, F., Endo, T., Dotani, T., Yokogawa, J., & Nishiuchi, M. 2002, ApJ, 579, 411

Pietsch, W., Rosso, C., & Dennerl, K. 1989, in ESA, Proceedings of the 23rd ESLAB Symposium, Volume 1: X Ray Binaries, 573

Sasaki, M., Haberl, F., & Pietsch, W. 2000, A&AS, 143, 391

Stevens, J. B., Coe, M. J., & Buckley, D. A. H. 1999, MNRAS, 309, 421

Tanaka, Y., Inoue, H., & Holt, S. S. 1994, PASJ, 46, L37

Yokogawa, J., Imanishi, K., Tsujimoto, M., Koyama, K., & Nishiuchi, M. 2003, PASJ, 55, 161

Table 1. The pulse period measurements of EXO 053109–6609.2

Date of Obs. (MJD)	Observatory - Instrument	Pulse period (s)	Reference
48560.16	ROSAT - PSPC	13.67133 ± 0.00005	Dennerl et al. (1995)
50228.12	ASCA - GIS	13.67875 ± 0.00012	Present work
50520.00	SAX - MECS	13.67590 ± 0.00008	Burderi et. al. (1998)
51107.64	SAX - MECS	13.670674 ± 0.000026	Present work
51600.72	SAX - MECS	13.66884 ± 0.00004	Present work
51824.56	XMM - MOS+PN	13.66817 ± 0.00001	Haberl et al. (2003)

Table 2. Spectral parameters of EXO 053109–6609.2 during different observations

Parameter	ASCA[a] 1996	SAX[a] 1997	SAX[a] 1998	SAX[a] 2000
N_H[b]	11^{90}_{-5}	$5.7^{+3.3}_{-0.0}$	29^{+230}_{-23}	$6.6^{+38}_{-0.9}$
Photon index (Γ_1)	$0.46^{+0.63}_{-0.37}$	0.81 ± 0.05	$0.37^{+0.54}_{-0.38}$	0.63 ± 0.17
Fe line flux[c]	-	3.0 ± 1.2	-	2.8 ± 2.5
log L_X [d]	36.09	36.78	35.48	36.18
Reduced χ^2/dof	0.23/9	1.44/79	0.49/20	0.55/46

[a]GIS2 + GIS3 for ASCA and LECS + MECS2 + MECS3 for SAX

[b]10^{20} atoms cm^{-2}

[c]10^{-5} photons cm^{-2} s^{-1}

[d]erg s^{-1}, 2.0-10.0 keV. Since the absorption column density is not well constrained, the L_X given here is not corrected for absorption

[e]10^{-13} erg cm^{-2} s^{-1}

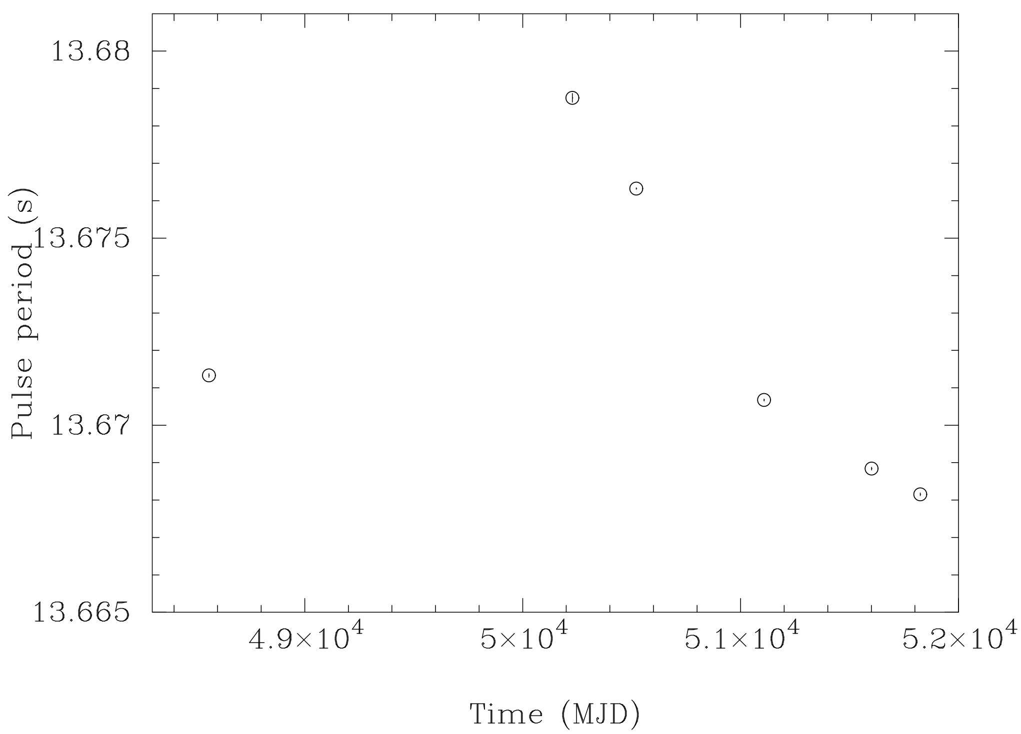

Fig. 1.— Pulse period history of EXO 053109–6609.2. The error bars lie within the circular symbols.

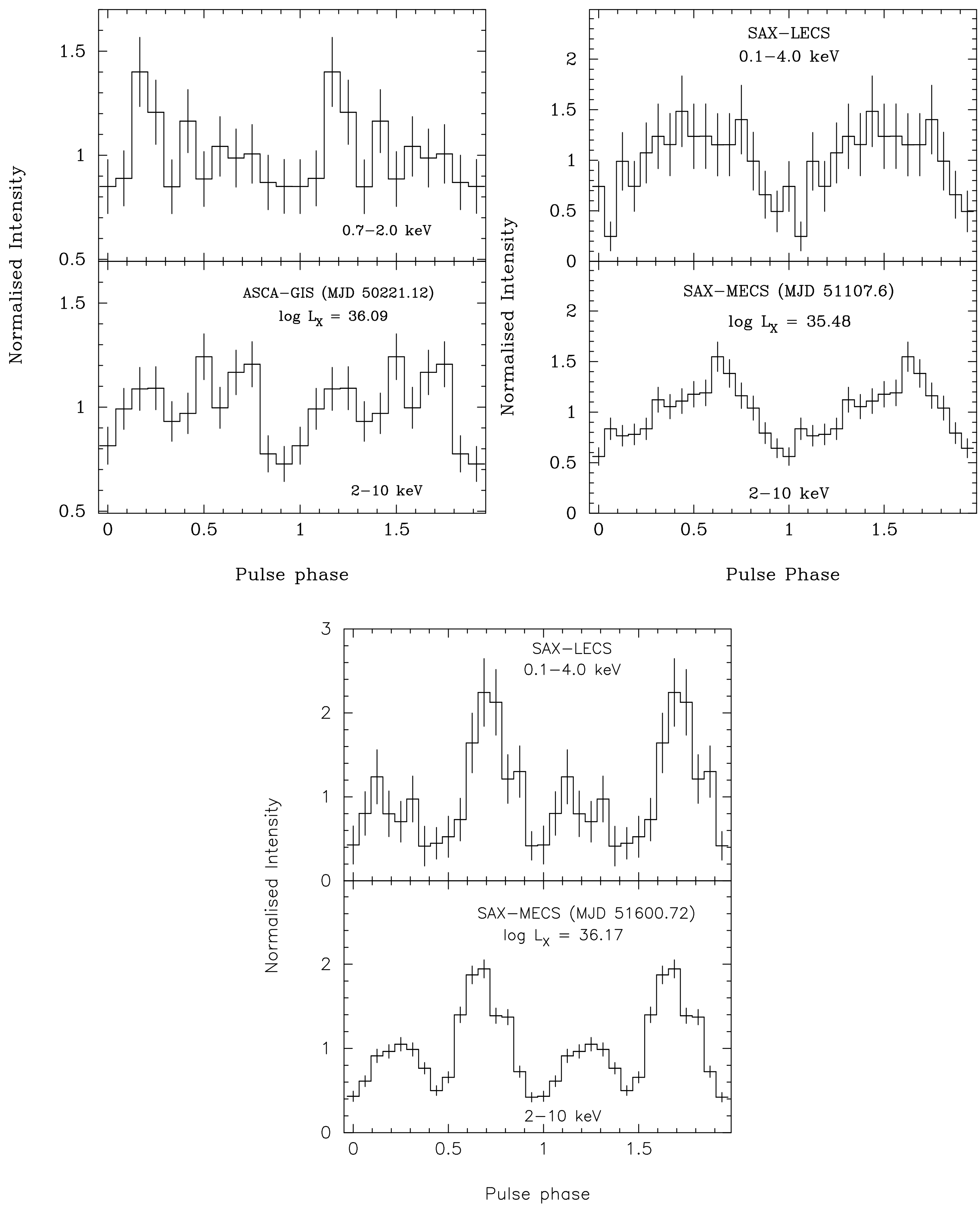

Fig. 2.— Pulse profiles of EXO 053109–6609.2 measured with the ASCA and Beppo-SAX detectors on various occasions are shown here.

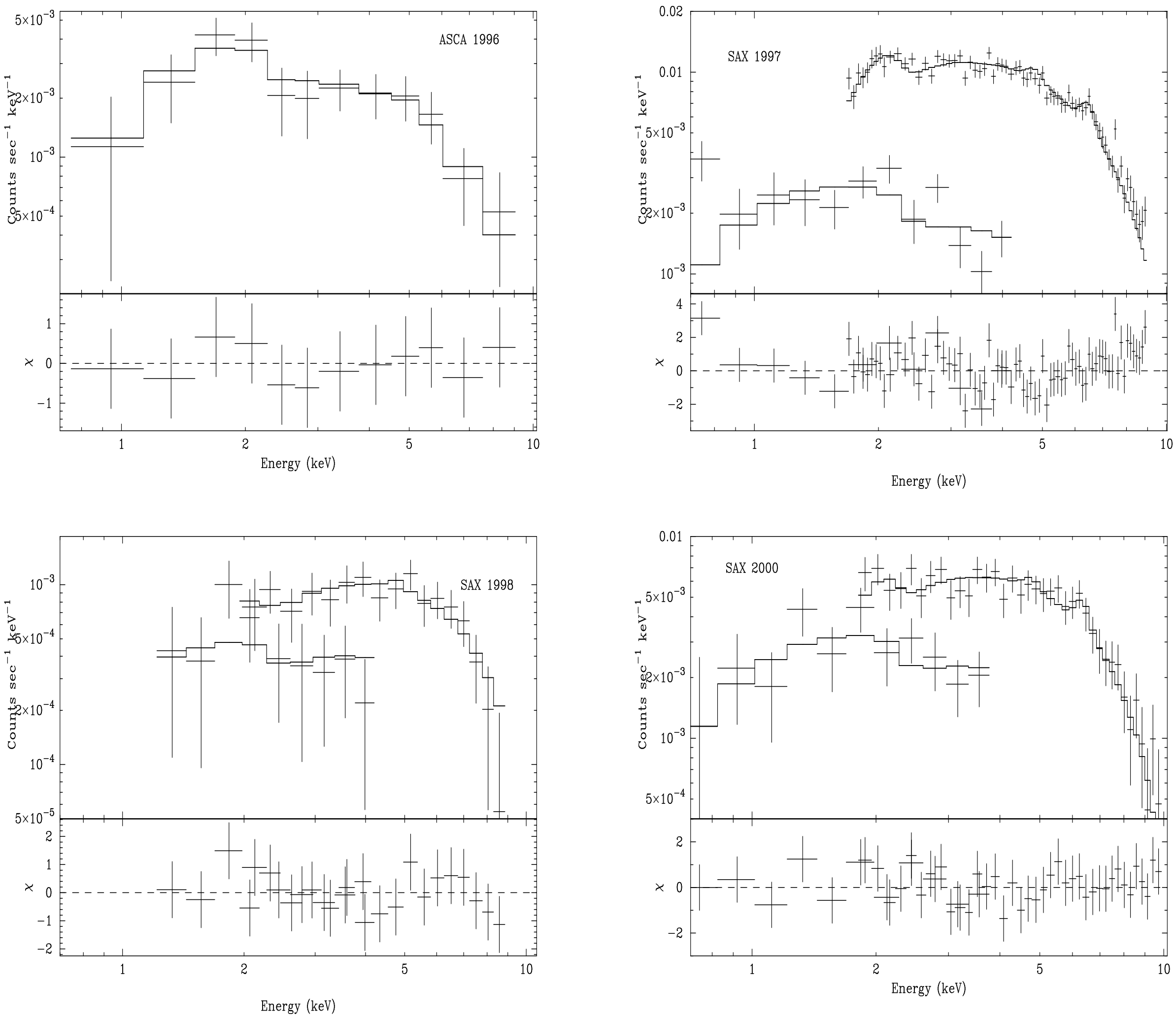

Fig. 3.— Energy spectra of EXO 053109–6609.2 measured with the ASCA and Beppo-SAX on various occasions along with the best fitted model spectra and the residuals.